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Batteries Charging Systems for Electric and Plug-In Hybrid Electric Vehicles

Vítor Monteiro, Henrique Gonçalves, João C. Ferreira and João L. Afonso

Additional information is available at the end of the chapter

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1. Introduction

Nowadays, energy efficiency is a top priority, boosted by a major concern with climatic changes and by the soaring oil prices in countries that have a large dependency on imported fossil fuels. A great part of the oil consumption is currently allocated to the transportation sector and a large portion of that is used by road vehicles. According to the international energy outlook report, the transportation sector is going to increase its share in world's total oil consumption by up to 55% by 2030 [1]. Aiming an improvement of energy efficiency, a revolution in the transportation sector is being done. The bet is in the electric mobility, mostly supported by the technological developments in different areas, as power electronics, mechanics, and information systems.

Different types of Electric Vehicles (EVs) are being developed nowadays as alternative to the Internal Combustion Engines (ICE) vehicles [2][3], namely, Battery Electric Vehicles (BEV), Plug-in Hybrid Electric Vehicles (PHEV), in its different configurations [3], and Fuel-Cell Electric Vehicles (FCEV). This chapter presents batteries charging systems for Electric and Plug-in Hybrid Electric Vehicles. To simplify the reading and to contribute to a simple understanding, from now on, in this chapter, it will be used the terminology of Electric Vehicle (EV) to define these two types of vehicles.

EVs are increasingly popular, as demonstrated by the numerous vehicles recently made available in the market by almost all automakers. The main energy storage systems of these vehicles are the electrochemical batteries, the ultracapacitors and the full-cells. However, taking into account nowadays limits of energy storage of those technologies, the vehicles have limited range autonomy. Different energy storage systems configurations can be implemented [3][4][5], however, the electrochemical batteries still are the most used technology to store energy. Nevertheless, they are usually used in conjunction with

ultracapacitors to store energy during transient moments, as during the vehicle regenerative braking. Actually, the ultracapacitors are used in this way to receive a significant amount of energy in a short time, and to provide this energy to the next acceleration, or to help charging the batteries.

The electrical power grids were not designed for this new type of load, which corresponds to the batteries charging systems of EVs, therefore the impact caused by the proliferation of EVs cannot be neglected [6]. The challenge is to rebuild the electrical power grids, as early as possible, as “smarter” as possible, and the most environmentally friendly as possible. To achieve these targets arise the Smart Grids, which are not characterized as a single technology or device, but rather as a vision of a distributed electrical system, supported by reference technologies, as integrated communications, Power Electronics devices, Energy Storage Systems (ESS), and Advanced Metering Infrastructures (AMI). The Smart Grids intend to reduce the energy costs, and simultaneously to achieve a sustainable balance between production and consumption, increasing the reliability of the power grids and the power quality of the electrical energy delivered to the loads.

As aforementioned, EVs represent a new type of load that introduces new problems, but that also brings new possibilities of actuation. The problems arise from the possibility of occurring simultaneous charging of a large number of vehicles, which can overload the power grid, and from the effects of non-sinusoidal current consumption of the batteries charging systems. Among the opportunities, stands the fact that these vehicles have enormous potential to regulate the consumption profile from the power grid, by smoothing the natural intermittency of the renewable energy sources, and ensuring the power grid stability in terms of voltage and frequency, if they allow collaboration with the electrical power grid to store and deliver energy of the batteries in parked vehicles. One factor which suggests that such benefits may exist relates to the fact that private vehicles are parked on average 93-96% of their lifetime, during which time each vehicle represents an idle asset [7]. So, the energy stored in EVs' batteries may be suitable for providing regulation services, spinning reserves and peak power demand. This interactivity between the vehicles and the power grid is expected to be one of the key technologies in the future of the Smart Grids and batteries charging systems, and is called Vehicle-to-Grid (V2G). The new paradigms of Smart Grids and V2G bring a profound change to the present systems. In [8] is presented one approach to the future of the power grids focusing the impact of PHEVs in Smart Grids, and in [9] is presented a concrete case of a technology to integrate EVs with Smart Grids.

To solve the aforementioned problems different approaches can be taken into account, among them can be implemented a coordinated charging of the EVs, or a regulation of the required power of the vehicles according to the power grid capabilities. Different authors present studies about how the charging systems affect the distribution power grid, and how they contribute to the degradation of the power quality. In [10] is presented a comparative study of the performance of two types of batteries charging systems, and in [11] is studied the effect of EVs batteries charging systems on a substation transformer that supplies

commercial, residential, and industrial loads during a peak of consumption in a summer day. A report published by the California Energy Commission [12] presents a study about the impact of residential EVs batteries charging systems. It shows that, for the use of the GM EV1 vehicle, the Total Harmonic Distortion (THD) of the current presents a variation from 3% (at the beginning of charging, with a unitary power factor) to 28.11% (at the end of the charging, with a power factor equal to 0.96). So, it is clear that the simultaneous use of a great number of EVs batteries charging systems connected to the electrical distribution grid can cause a significant degradation of the electrical power quality. In the particular case of Portugal, in [13] is analyzed the impact of PHEVs in the electric utility system, where it is approached a Portuguese consumption profile. These studies have only considered the Grid-to-Vehicle operation (G2V) since it is expected that this is the first scenario that will be found. The impacts of the batteries charging rates of EVs on the Smart Grid distribution systems are approached in [14]. For this goal were compared different charging rates, during different charging periods along a day. It was also considered the existing system load profiles, and it was evaluated the overall performance of the electrical distribution system. The integration of EVs in the power grid is approached in several papers in the literature (e.g., [15]), as well as the integration of PHEVs in different parts around the world, like China, [16]. In [17] is analyzed the impact of EVs in an isolated electrical power grid.

The power quality is an important issue in order to ensure the proper functioning of the power grid system and the loads connected to it. These requirements should be a characteristic of both parts of the system: the energy supplied by the power grid, as well as the energy consumed by the equipment connected to the grid [18]. Besides the harmonics, other power quality problems, as inter-harmonics, noise (electromagnetic interference), momentary interruptions, sags, swells, flicker, notches, and transients can also occur [19][20]. But in what regards the integration of the electric mobility in a Smart Grid, the degradation of the power quality is mainly caused by the non-linear current consumption of the batteries charging systems. This is reflected in the THD of the consumed current and also in the voltage THD, due to the line impedance [21]. As a way to mitigate these problems, the EVs' batteries charging systems should have sinusoidal current consumption and unitary power factor. This is true for both home chargers and public charging stations.

2. Smart Grid: Electric mobility integration

It is predictable that in the near future, in a real full scale Smart Grid scenario, the power grid should meet the increasing demand of energy in a reliable and efficient way, maintaining the required stability and interfacing renewable energy resources, as a large network of microgrids.

Figure 1 shows a draft of a scenario for a micro Smart Grid with: a microgeneration power station with solar photovoltaic panels and micro wind turbines (which produce energy); some EVs with G2V and V2G capabilities (which can receive or provide electrical energy);

and Energy Storage Systems (which, like the EVs, can receive or provide electrical energy). Beyond the flow of energy between the parts, there is also the sharing of information, controlled by a Collaborative Broker [22]. In this figure are also shown the blocks of the Maximum Power Point Trackers (MPPTs) (for the micro solar photovoltaic panels and micro wind turbines), and the blocks of the AC-DC and DC-AC converters to adjust the levels of the voltages and the currents between both sides [23].

Communication and Management of a micro Smart Grid

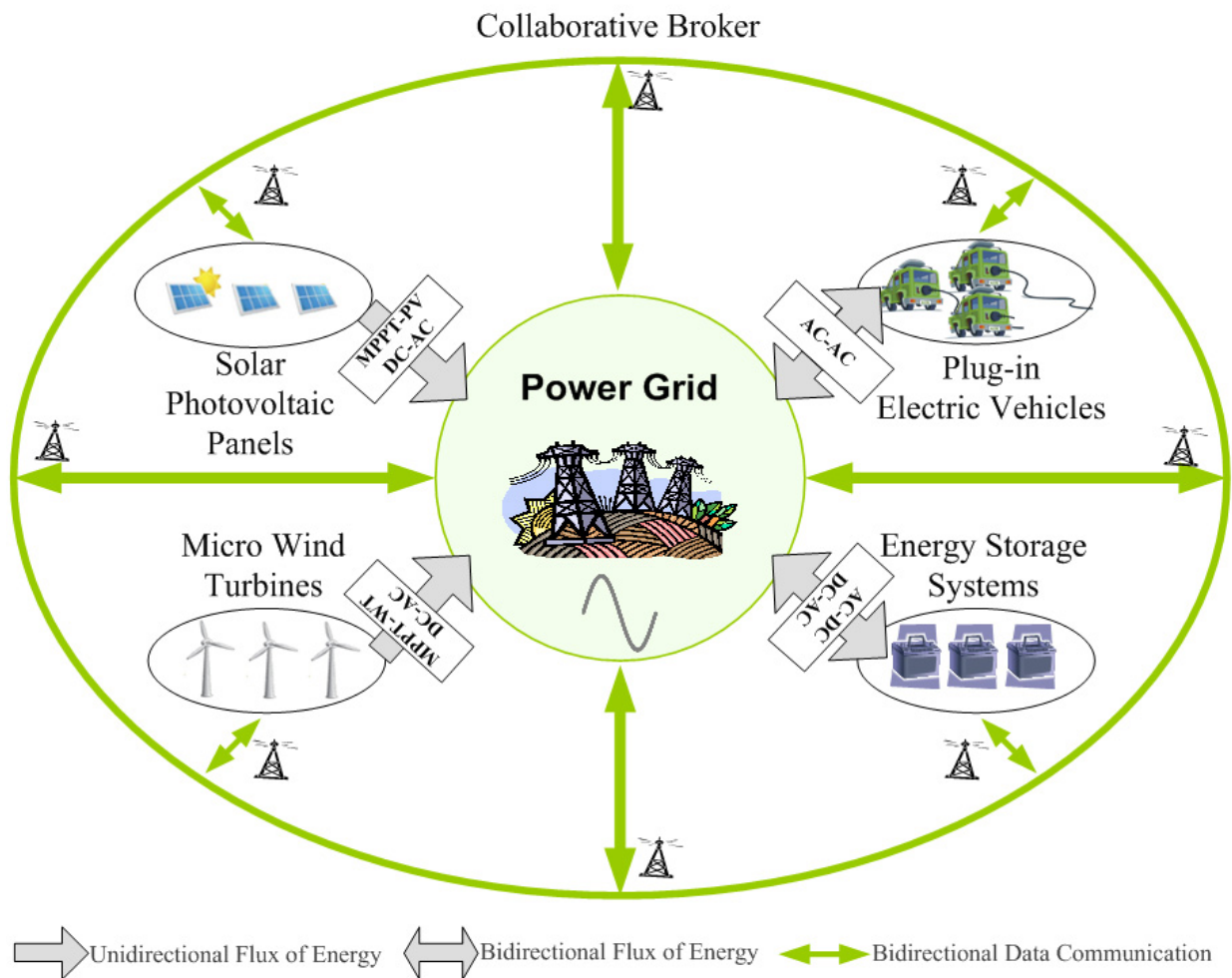


Figure 1. Scenario of a micro Smart Grid.

Such power grid scenario, with the EVs smart charging systems, will allow the communication of the vehicles with the local utilities to ensure that the batteries are charged when the electricity is cheapest and the impact of the charging systems on the grid is smallest. The use of computerized charging stations which constantly monitor the EV charging process, in order to optimize the charging rate, will be of extremely important to preserve the batteries lifespan. In Figure 2 is shown in detail the integration of EVs (in a typical charging park) with microgeneration renewable energy sources (solar photovoltaic panels and micro wind turbines), and Energy Storage Systems (ESS), in a Smart Grid context.

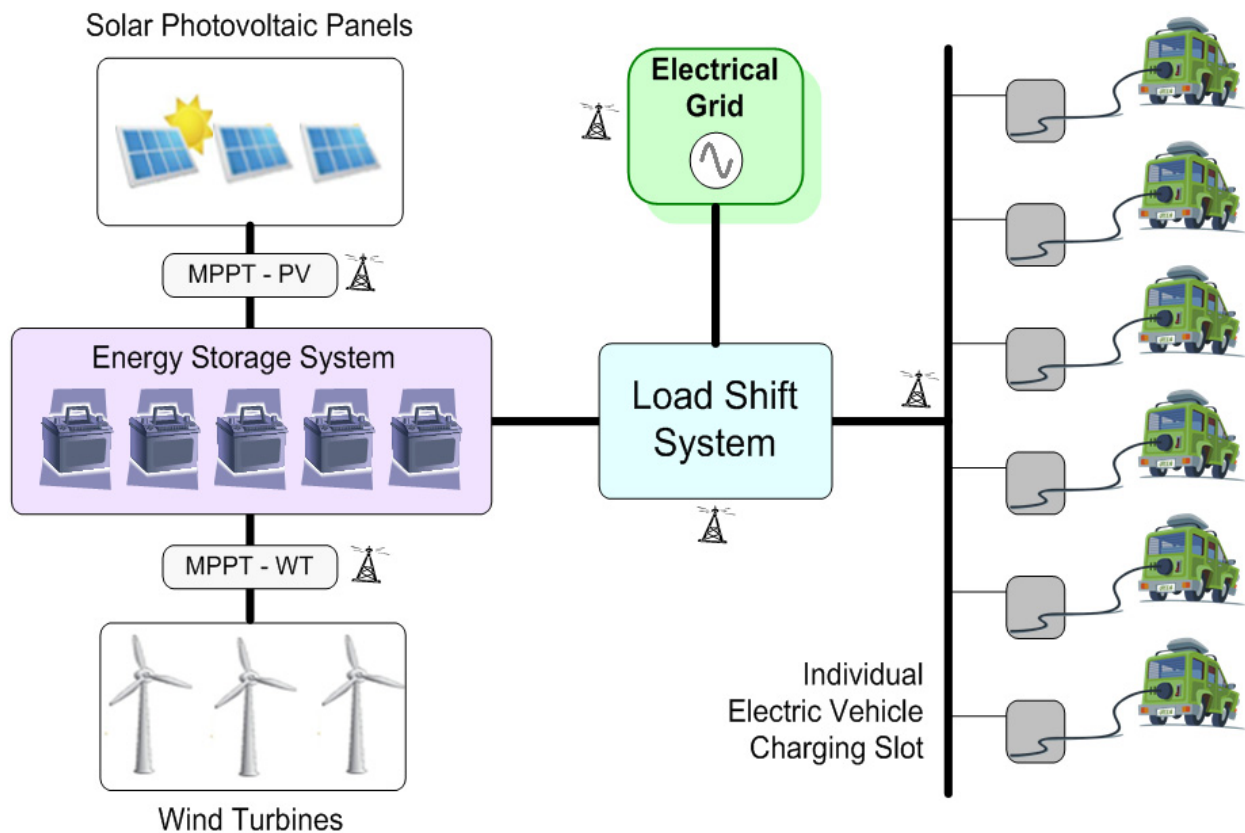


Figure 2. Integration of Electric Vehicles, renewable energy sources (solar photovoltaic panels and micro wind turbines), and Energy Storage Systems (ESS), in a Smart Grid context.

2.1. Interaction modes with Electric Vehicles

As mentioned before, enormous advantages arise from the interaction of EVs with the power grid. Focusing the interaction of EVs with the different systems where they can be connected, several concepts can be defined.

2.1.1. Grid-to-Vehicle

The concept of Grid-to-Vehicle (G2V) is the simplest process of integration of the EVs batteries charging system with the power grid. It is not required any communication between both systems and only exists energy flow from the power grid to the EVs. Nowadays, this is the most common (and almost unique) batteries charging process for EVs, and it will be the first approach to the massive integration of these vehicles.

2.1.2. Vehicle-to-Grid

As defined by Mid-Atlantic Grid Interactive Cars Consortium (MAGICC) [24], Vehicle-to-Grid (V2G) technology utilizes the stored energy in the EVs batteries to contribute with electricity back to the electrical power grid, when the grid operators request it. This way the

EVs can receive energy during the excess of production and deliver it back to the power grid during the periods of great demand, balancing the energy production and consumption, and also stabilizing the intermittency production from renewable energy sources, improving their integration into the power grid. Thus, V2G is described as a system where EVs can communicate with the power grid to sell or to buy energy, in order to establish the power demand [25]. To make it possible the batteries charging system needs assistance of an intelligent and collaborative system to control both processes, and also to add extra functionalities, as finding the periods with cheaper prices to charge the batteries, to identify available charging slots in public areas, and to provide useful information to the drivers. Each vehicle should have two fundamental elements: a connection for the bidirectional flow of the electrical energy; and a logical connection for the communication and control in both sides. The control signal from the power grid operator to the vehicles can be implemented through a broadcast radio signal, through a cell phone network, through an internet connection, or through Power Line Communication (PLC) [26].

2.1.3. Vehicle-to-Home

The concept of Vehicle-to-Home (V2H) is similar to the V2G concept; however it can avoid the grid infrastructure and the electricity tariff problems associated with V2G, because the bidirectional flux of energy is between the vehicle and the house. Thereby, V2H can be used to manage and regulate the profile of electricity demand in a house, controlling the use of the loads and the stored energy available in the vehicle. It also can be used out of the power grid, in isolated electrical systems, and in conjunction with renewable energy sources, increasing their effectiveness.

2.1.4. Vehicle-to-Building

A specific version of V2G, denominated Vehicle-to-Building (V2B), is a concept that consists in using the stored energy in the batteries of EVs as an energy source of back-up to compensate the energy consumption profile in a commercial scale (e.g., in companies and shopping center parks).

2.2. Batteries charging process

As previously commented, and as demonstrated in [27], the load profile of the EVs batteries charging systems has high importance to the power grid management. Depending on the design of the electrical grid and the type of charging and discharging processes, EVs can be a problem or a benefit to the power grid. The batteries charging and discharging processes can be realized in two different ways: controlled and uncontrolled.

In the controlled way, the batteries are charged or discharged in accordance to the capability and the needs of the power grid, and in accordance with the conveniences of the vehicle's owner, which is the main figure in this process. In this scenario of real time control, several parameters should be taken into account, namely, energy price (to sell or to buy) and batteries State-of-Charge (SoC) and State-of-Health (SoH - reflects the batteries degradation

along their lifetime). In [28] is proposed an autonomous distributed V2G control scheme, and in [29] is presented a coordinated charging scheme for multiple PHEVs in a residential distribution grid. Some technical solutions for the integration of EVs in the electrical power grid can be found in [30].

In the uncontrolled way, as the name suggests, there is no control over the charging system. The only control that exists from the moment in which the vehicle is plugged to the end of the process, is the decision if the process of charging or discharging can start immediately or after a fixed time delay (controlled by the vehicle's owner in accordance with his convenience). Since there is no control over the charging systems, peaks of power consumption can occur in the electrical power grid, during some periods in which exist a large number of EVs simultaneously charging their batteries. These power peaks can bring overload problems to the power grid. Similar problems can occur when the energy stored in the batteries is delivered back to the electrical power grid. Despite these problems, nowadays, the uncontrolled way is the most common charging procedure. As predicted in [31], in Portugal, the smart charging (in controlled way) will be a necessity in midterm, in order to prevent a large demand of energy peaks over the power grid.

2.3. Types of access

The batteries charging systems can be of two types: public chargers and residential chargers. Public chargers are an optimal solution to charge the batteries of the vehicles using energy from several sources of energy (as wind or sun) and can be deployed at strategic places around a town or city, like for example, at companies, public buildings and shopping centers parking lots. On the other hand, residential chargers are designed to deliver low power, in an efficient way, since in general they are used to make a complete charge of the batteries during long periods of time (slow charging). The main benefits of these two types of chargers are the comfort for the user, and the freedom of the user to charge the batteries when he wants, according with the best prices of energy. The main disadvantage is that, since each charging process is independent, the limit of overload of the electrical power grid can be easily reached.

2.4. Charger specifications

Currently, the majority of EVs are designed with on-board unidirectional batteries charging systems. Besides the on-board batteries charging systems, some vehicles allow the charge of their batteries with off-board chargers. An on-board batteries charging system refers to a charger implemented inside the vehicle. The user only has access to the input of the charging system. This type of charger is connected to the AC electrical grid voltage and is used to slowly charge the batteries – it is denominated as “slow charging”. On the other hand, an off-board batteries charging system is implemented outside the vehicle. It is given access to the DC voltage of the batteries and is used to charge the batteries as fast as possible – it is denominated as “fast charging”.

Regarding the way that the charger can be connected to the vehicle, there are two different approaches: conductive or inductive. The conductive batteries charging system is made

through a physical contact between the vehicle and the power grid. In counterpart, with the inductive batteries charging system there is no physical contact between the vehicle and the power grid. Independently of the charger type, the interaction between the EVs and the power grid should comply with regulatory standards, as the International Electrotechnical Commission (IEC) norms (IEC 62196 and IEC 61851).

3. Electric vehicles batteries charging systems

As aforementioned some vehicles allow the charge of their batteries with off-board batteries charging systems, like public charging stations, but almost every vehicle is equipped with its own on-board batteries charging systems. This charging system is an AC-DC power circuit that must be controlled in order to respect the vehicles’ batteries nominal characteristics to preserve their lifespan. Additionally, it should monitor the batteries during their operation to prevent damages during the charging or discharging processes. The AC-DC power circuit can be implemented with different topologies according to the characteristics desired for the system. Figure 3 illustrates graphically the main categories in which can be divided the different topologies of the batteries charging systems for EVs.

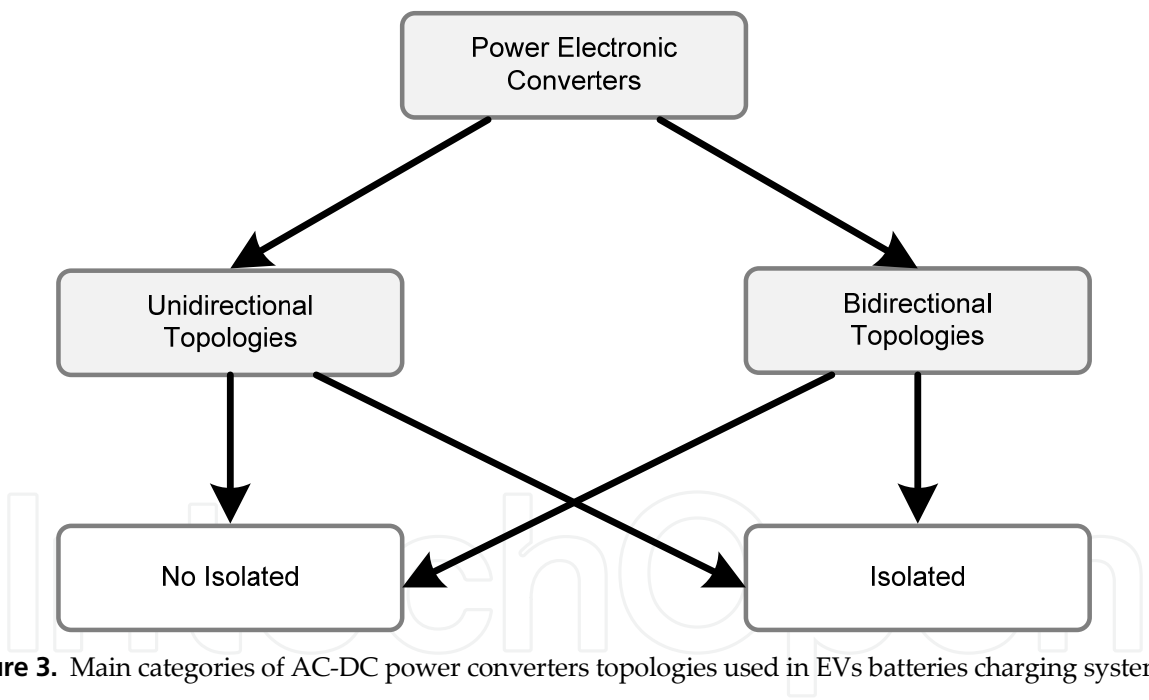


Figure 3. Main categories of AC-DC power converters topologies used in EVs batteries charging systems.

3.1. Power electronics circuits topologies

Typically, the power electronics circuit topology of batteries charging systems is formed by two power electronics converters: an AC-DC converter followed by a DC-DC converter. Both power converters can have different topologies and can be arranged together in different ways, with and without isolation between them. The AC-DC converter is used to rectify the AC voltage from de power grid to a DC voltage. The DC-DC converter is used to adapt the rectified voltage to a level of voltage compatible with the batteries’ voltage and

also to control the batteries charging process. In Figure 4 is shown the main AC-DC power converters topologies used to rectify the power grid AC voltage, and in Figure 5 is shown the main DC-DC power converters topologies used to control the batteries charging and discharging processes.

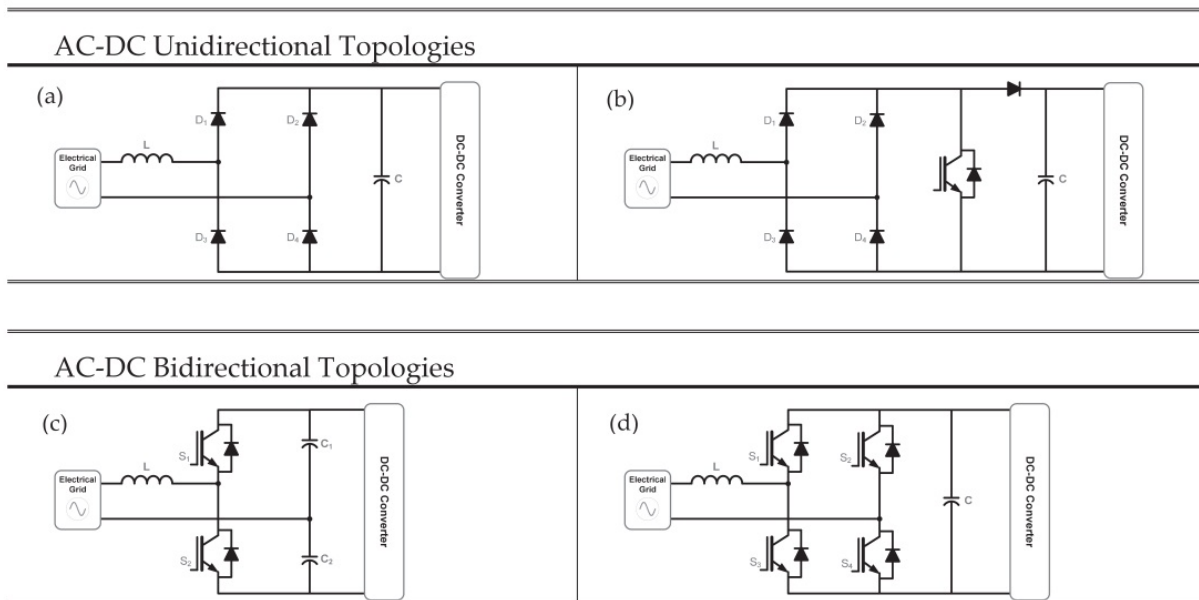


Figure 4. Main AC-DC power converters topologies used in EVs batteries charging systems: (a) unidirectional full-bridge non-controlled converter; (b) unidirectional full-bridge non-controlled converter followed by a boost converter; (c) bidirectional half-bridge full-controlled converter; (d) bidirectional full-bridge full-controlled converter.

The simplest AC-DC power converter uses diodes as rectifying components, as illustrated in Figure 4 (a). It is easy to implement, cheap to construct, and less susceptible to damages. However, the output voltage, and the consumed current are not controlled and consequently, the waveform of the consumed current is not sinusoidal, and so this type of converter contributes to the degradation of the electrical grid power quality. On the other hand, using power switching semiconductors is possible to control the waveform of the consumed current, as well as the output voltage. When compared with the AC-DC power converter with diodes, it has the disadvantages of having a more complex power electronics circuit and control system (which can be digital or analogue, and higher implementation and maintenance costs. Nevertheless, it has the advantage of the sinusoidal current consumption that does not degrade the power grid quality. The AC-DC power converter presented in Figure 4 (b) adds to the diodes rectifier a DC-DC boost converter that will make the Power Factor Correction (PFC). With this topology, it is possible to control the waveform and the power factor of the consumed current. Despite being a good alternative to control the waveform of the consumed current, it has the disadvantage of only operating in unidirectional mode (G2V). To make possible a bidirectional energy flow it is necessary a topology like the one presented in Figure 4 (c) and (d). The difference between these two

converters is the number of power semiconductors and capacitors, and the resulting level of the output voltage. The level of the output voltage of the converter presented in Figure 4 (c) is the double of the converter presented in Figure 4 (d).

The most basic topology of DC-DC power converter used in batteries charging systems is the DC-DC buck converter. This topology, presented in Figure 5 (a), is not isolated and only allows the unidirectional operation (G2V). Combining the structure of this topology with the structure of a DC-DC boost converter it is possible to obtain a bidirectional topology, as shown in Figure 5 (c). During the batteries charging process, the energy flows from the power grid to the batteries (G2V), and the converter operates as a DC-DC buck converter. When the energy flows from the batteries to the power grid (V2G), the converter operates as a DC-DC boost converter. If it is wanted galvanic isolation it should be used high frequency transformers. In Figure 5 (b) is presented an isolated unidirectional topology of DC-DC converter, and in Figure 5 (d) is presented an isolated bidirectional topology of DC-DC converter. As it is noticeable, when compared with the non-isolated topologies, these isolated topologies use a greater number of power semiconductors, and besides, their control systems are more complex.

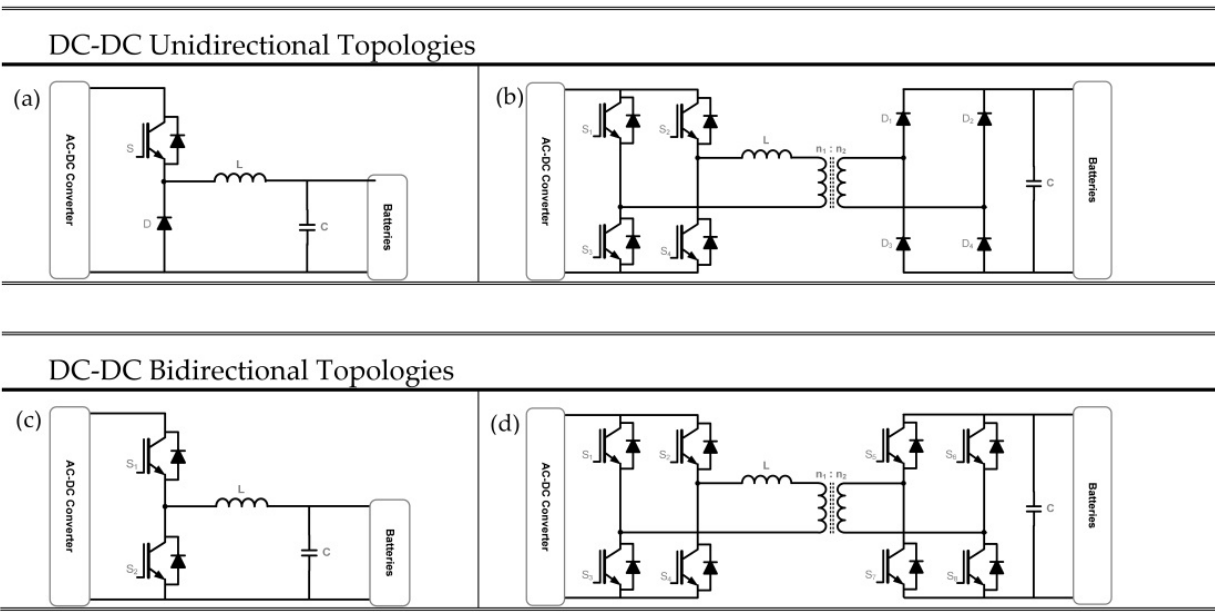


Figure 5. Main DC-DC power converters topologies used in EVs batteries charging systems: (a) unidirectional buck converter; (b) unidirectional isolated converter; (c) bidirectional buck boost converter; (d) bidirectional isolated converter.

The typical structure of an EV batteries charging system results from the combination of the AC-DC and DC-DC converters with the respective digital control system. For an appropriate control it should be measured the voltage and current in the power grid side, the DC link voltage, and the voltage and the current in the batteries. In Figure 6 is presented a block diagram with both converters, the digital control system and the points of measurement.

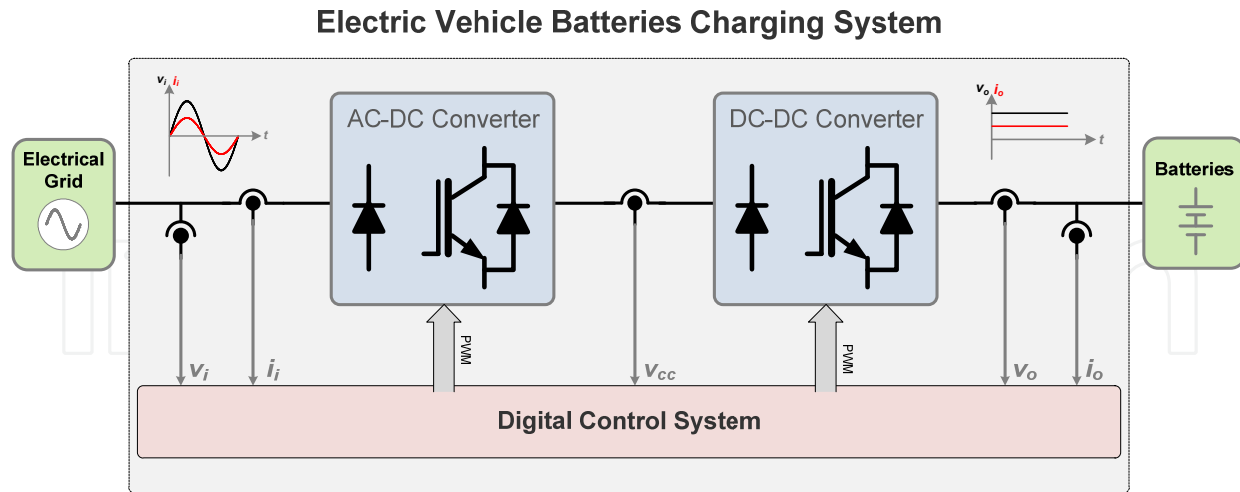


Figure 6. Structure of an Electric Vehicle batteries charging system.

3.2. Typical waveforms

For better understanding the influence of the AC-DC power converters topologies in the power grid quality, it should be analyzed their typical waveforms, with and without sinusoidal current consumption. The typical waveform of the current consumed by a conventional AC-DC power converter, without sinusoidal current consumption, presented in Figure 4 (a), is shown in Figure 7. It is visible that the current is not sinusoidal. Due to the line impedance the power grid voltage waveform is also affected. The harmonic spectrum of this current is shown in Figure 8. The Total Harmonic Distortion (THD) of the consumed current is 77.9%.

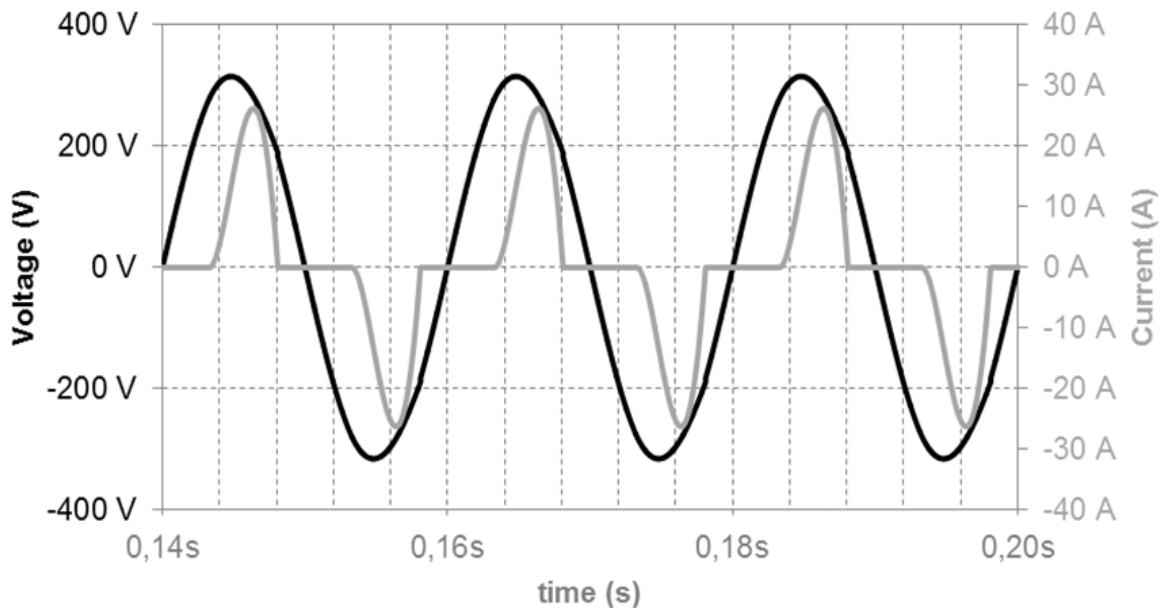


Figure 7. Typical waveforms of a conventional AC-DC power converter.

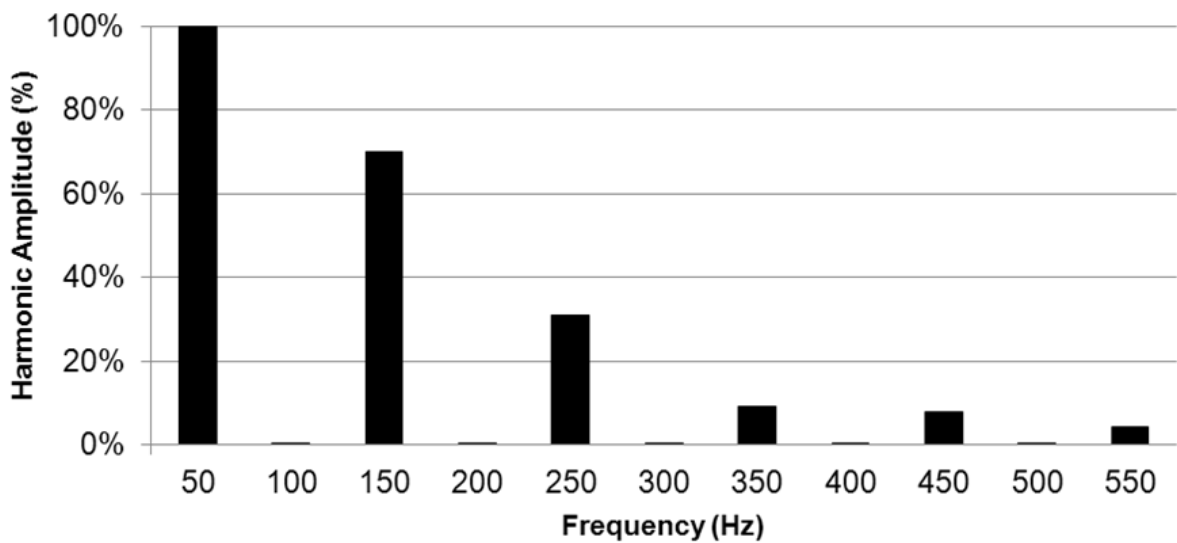


Figure 8. Harmonic spectrum of the current waveform of a conventional AC-DC power converter.

The typical waveform of the current consumed by AC-DC power converters with sinusoidal current consumption, presented in Figure 4 (b), (c), and (d), is shown in Figure 9. As illustrated, the current waveform is sinusoidal and with unitary power factor. The harmonic spectrum of this current is shown in Figure 10. The THD% of this consumed current is 0.4%.

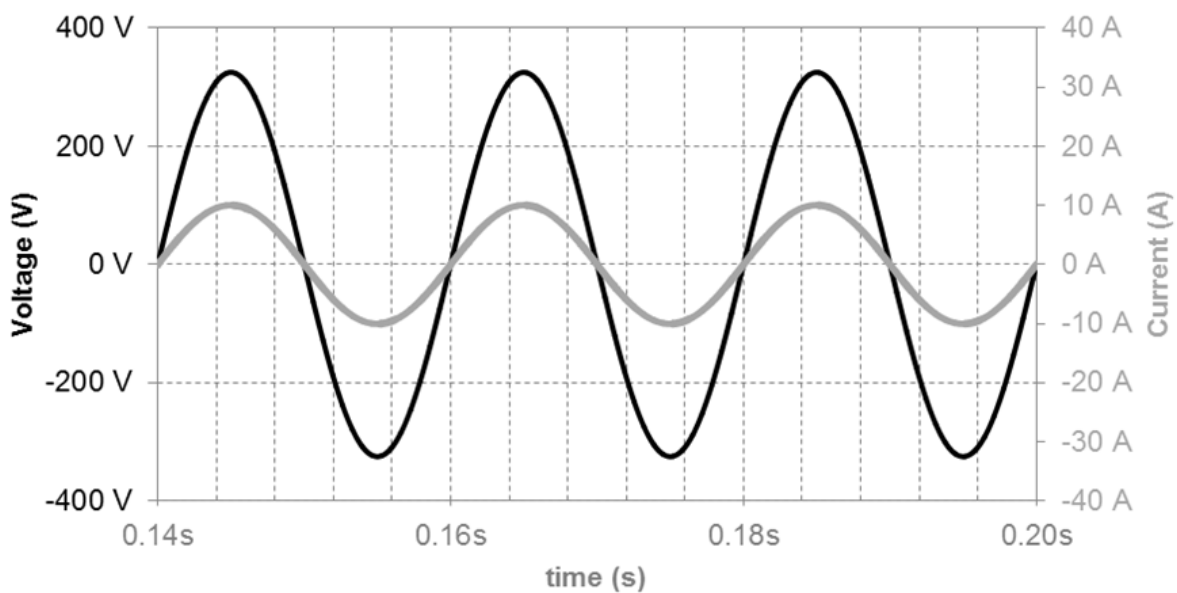


Figure 9. Typical current waveform of an AC-DC power converter with sinusoidal current consumption.

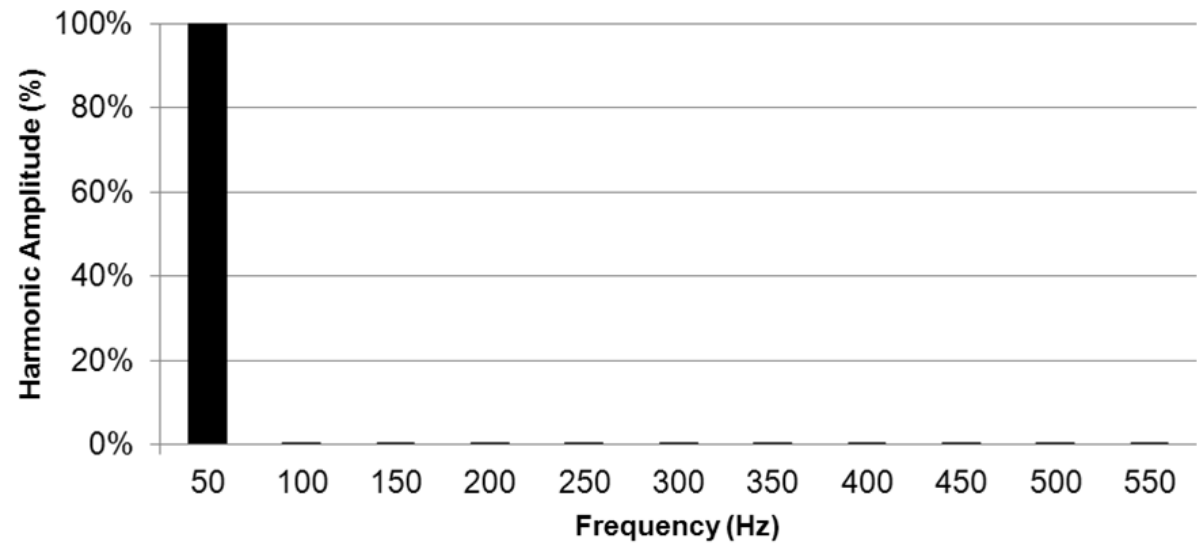


Figure 10. Harmonic spectrum of the current waveform of an AC-DC power converter with sinusoidal current consumption.

Taking into account the predictable increase in the utilization of EVs, the AC-DC power converters with sinusoidal current consumption are more appropriate to be implemented in the batteries charging systems of these vehicles. During the V2G process, when the energy stored in the batteries is delivered back to the power grid, it is also important to have control over the current. The typical current waveform during this process is presented in Figure 11. The harmonic spectrum of this current is shown in Figure 12. The THD% is 0.7%. As illustrated, the current is in phase opposition with the voltage of the power grid.

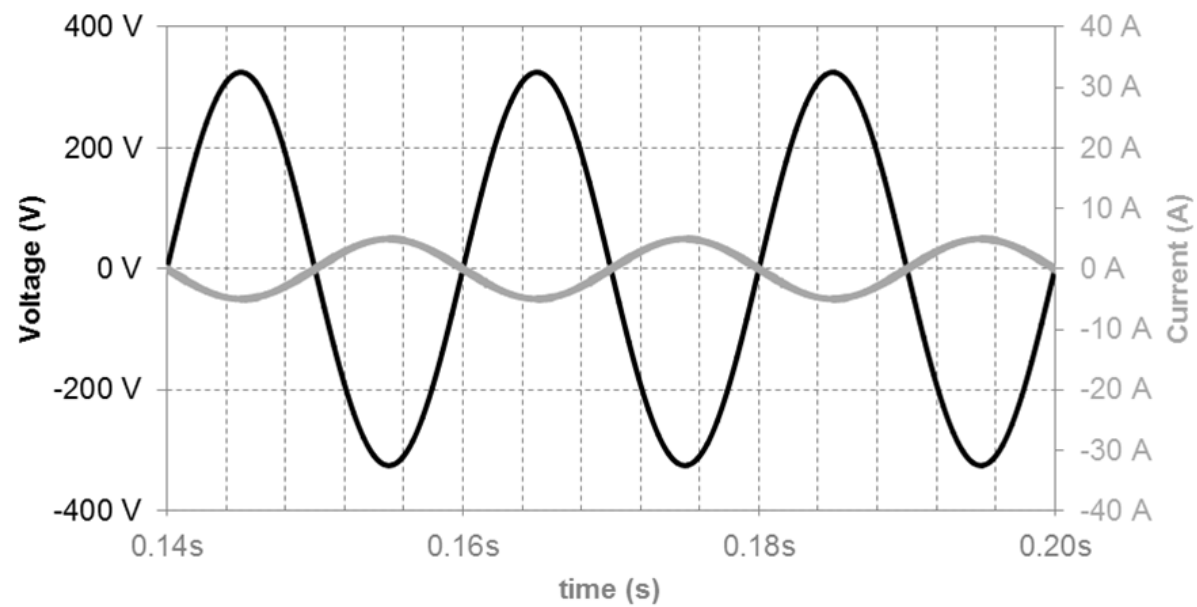


Figure 11. Typical current waveform of an AC-DC power electronic converter with sinusoidal current, delivering energy back to the power grid.

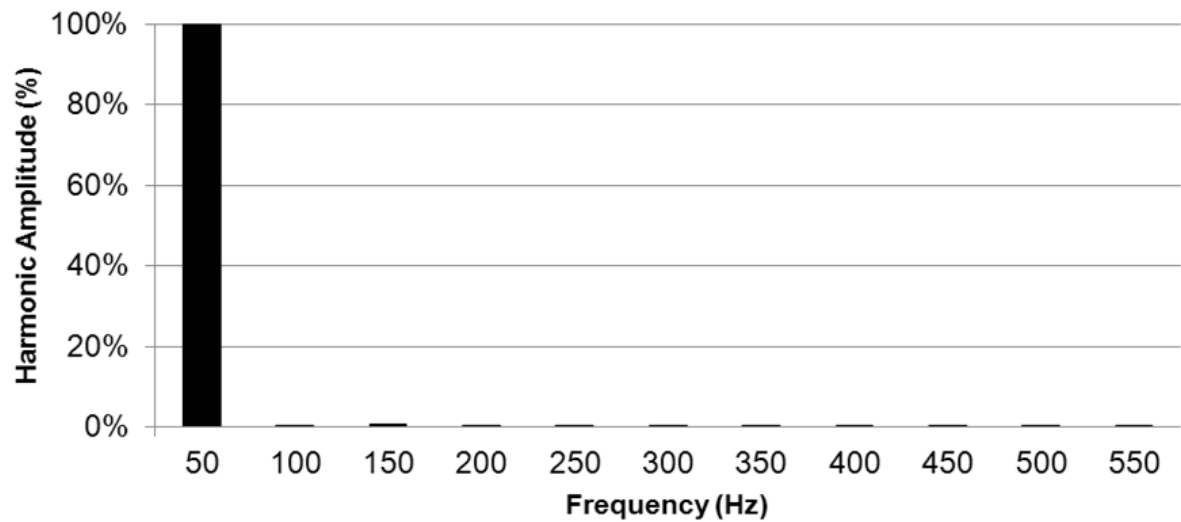


Figure 12. Harmonic spectrum of the typical current waveform of an AC-DC power converter with sinusoidal current, delivering energy back to the power grid.

4. Developed electric vehicle batteries charging system

It was developed a laboratory prototype of a 3 kW batteries charging system that works with sinusoidal current consumption and unitary power factor, and that allows the charging of the batteries with different algorithms: constant-voltage, constant-current, and constant-current followed by constant-voltage; in accordance with the State-of-Charge (SoC) level of the batteries and with their technology, namely, lithium, nickel, and lead-acid. Figure 13 shows the schematic of the developed batteries charging system.

This batteries charging system also allows bidirectional flow of energy between the power grid and the batteries, operating in both modes with sinusoidal current, and therefore, it can

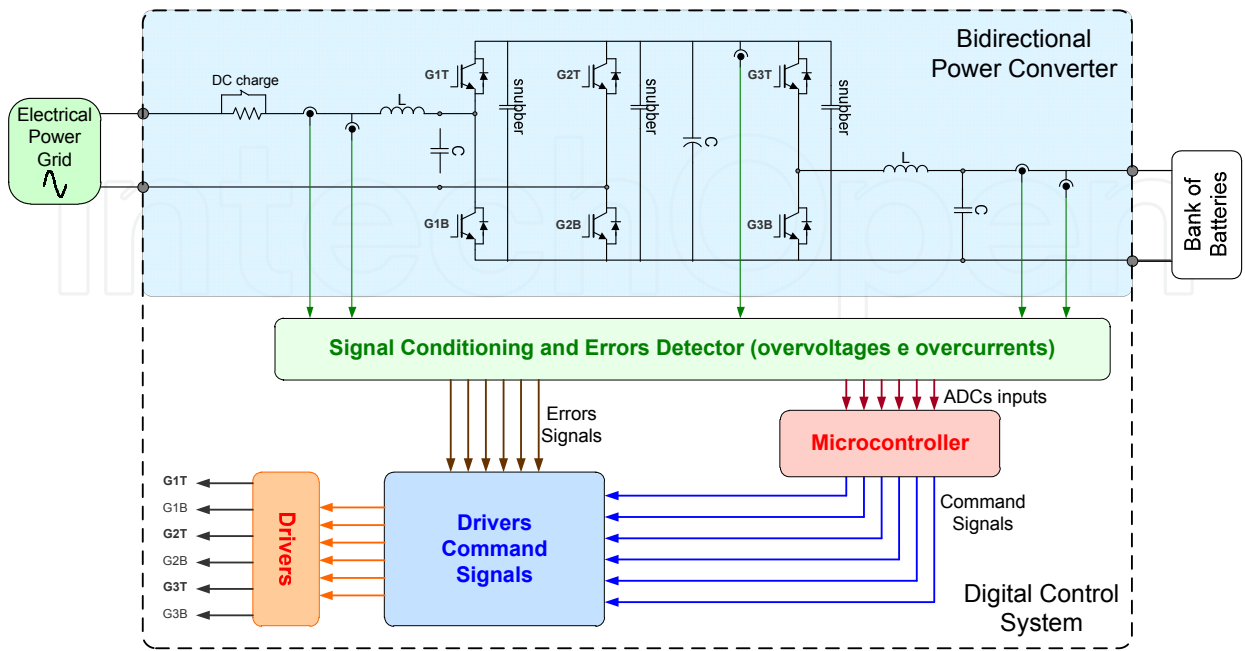


Figure 13. Schematic of the developed Electric Vehicle batteries charging system.

be considered as a smart charger. As illustrated in Figure 13, it is constituted by two main parts: the bidirectional power converter, which uses inductances, capacitors and IGBTs as switching power semiconductors; and the control system, that is constituted by the microcontroller, the signal conditioning circuit, the command drivers and the drivers.

4.1. Laboratory prototype

The laboratory prototype of the implemented smart EV batteries charging system is shown in Figure 14. In this figure can be seen the different parts of the developed smart charging system,

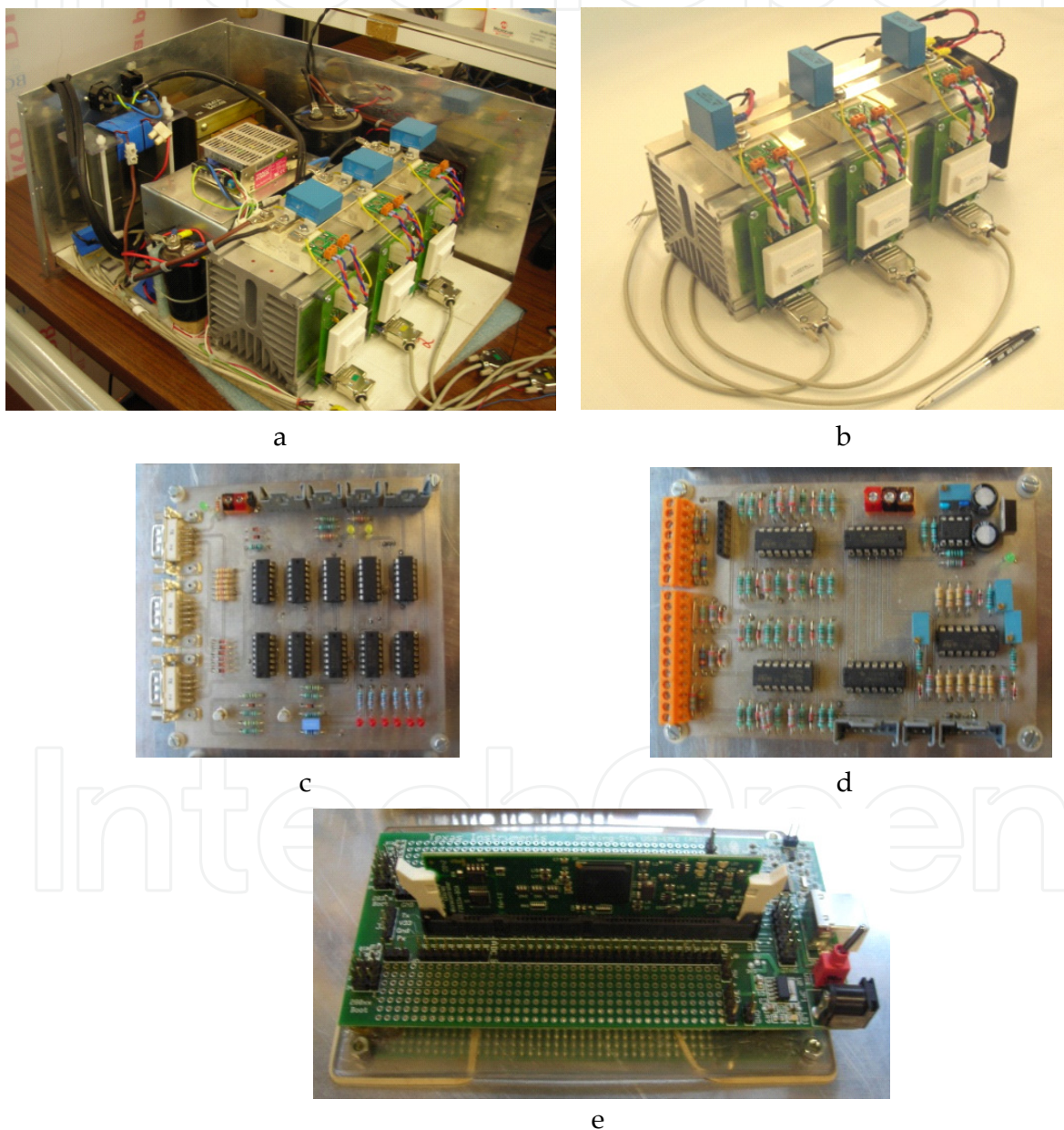


Figure 14. Developed smart charging system for Electric Vehicle batteries: (a) Charging system overview; (b) AC-DC and DC-DC Bidirectional power converters; (c) Command drivers board; (d) Signal conditioning and errors detector board; (e) Microcontroller DSP TMS320F28335 board.

namely: the bidirectional power converters, the IGBTs drivers, the command drivers board, the conditioning and errors detector board, and the microcontroller DSP TMS320F28335.

4.2. Experimental results

This laboratory prototype was tested for different conditions of operation. In Figure 15 are presented the power grid voltage and the current consumed in steady state by the batteries charging system. As it can be seen the consumed current is sinusoidal and in phase with the power grid voltage. Figure 16 shows the waveforms of the power grid voltage and current during the functioning as V2G. Since the vehicle is providing energy back to the power grid the current is in phase opposition to the voltage. The power quality specifications are fulfilled, and the current is sinusoidal.

Figure 17 presents the results obtained with the same batteries charging system, but operating as a conventional charger (without sinusoidal current consumption). It is possible to see that a conventional batteries charging system consumes highly distorted currents.

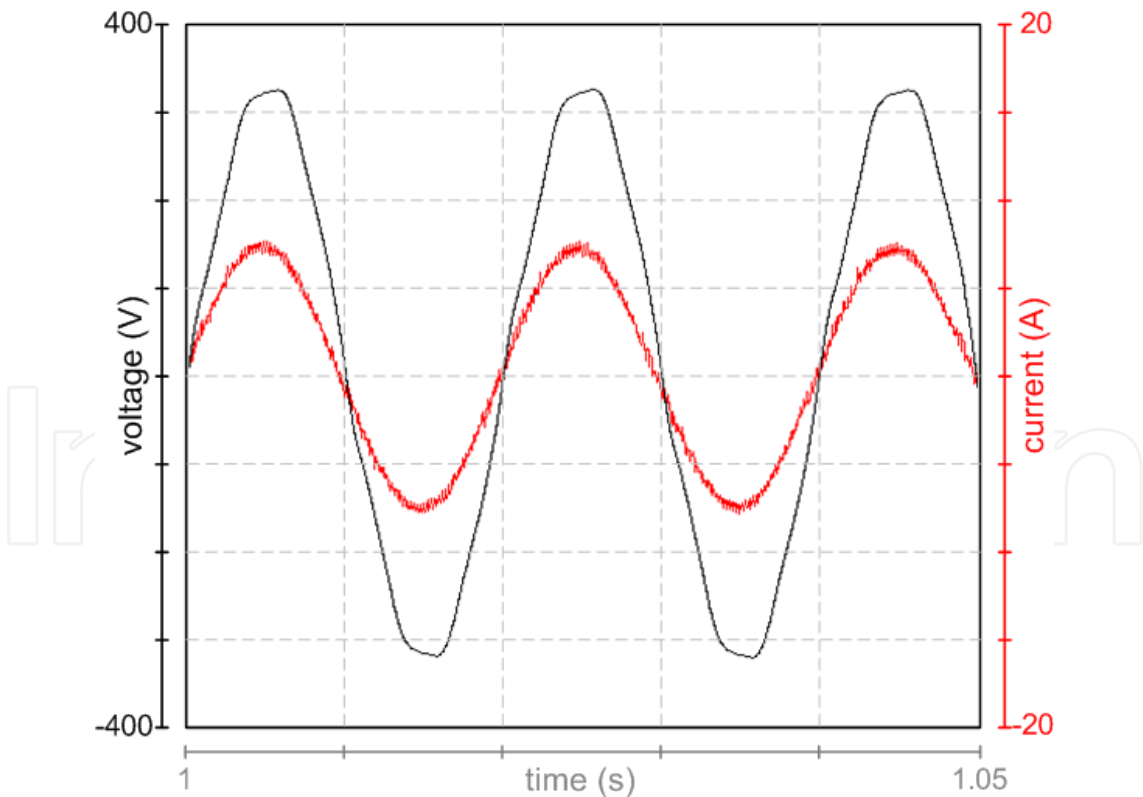


Figure 15. Experimental results: electrical grid current and voltage (in phase) during batteries charging - operation as G2V.

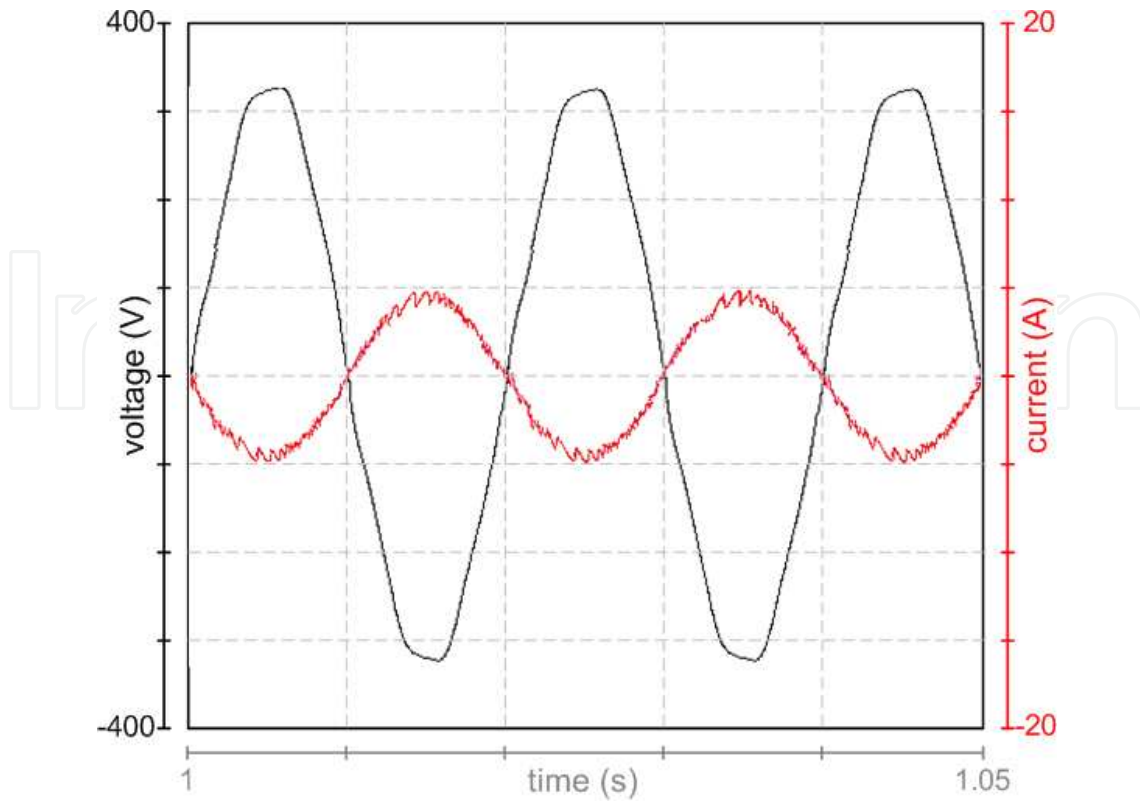


Figure 16. Experimental results: electrical grid current and voltage (in phase opposition) during batteries discharging - operation as V2G.

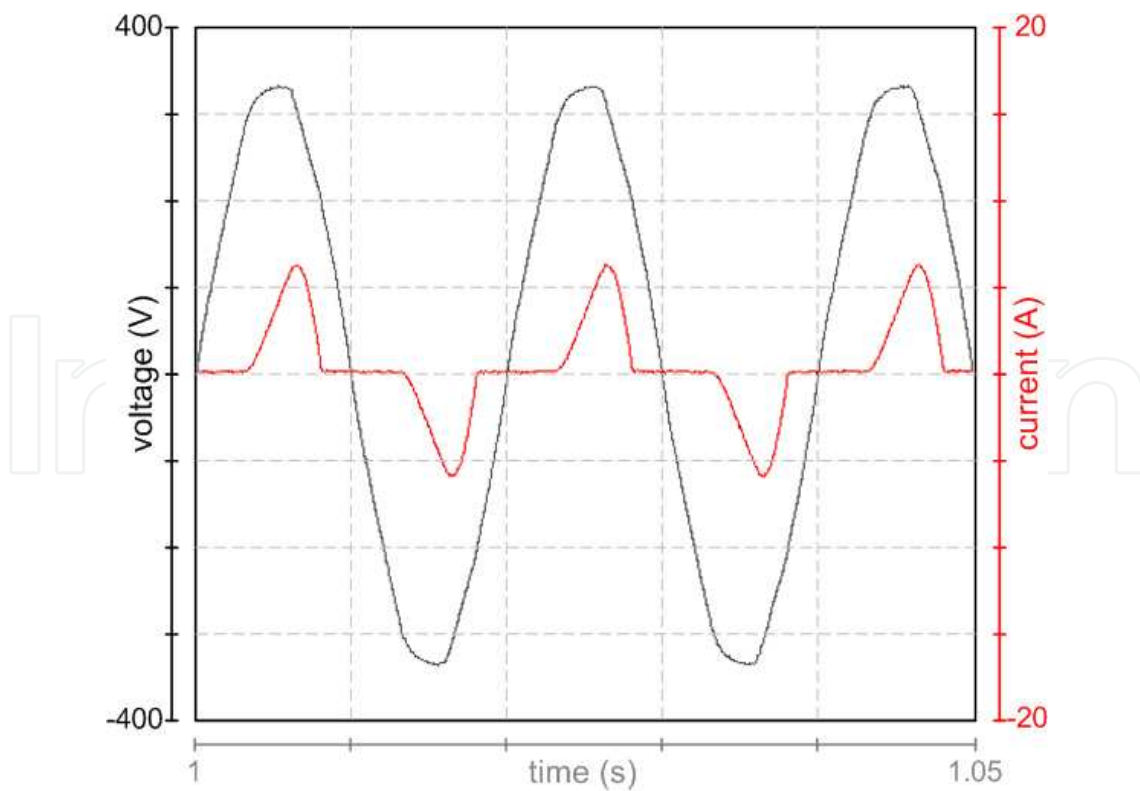


Figure 17. Experimental results: electrical grid current and voltage with a conventional charger during batteries charging - operation as G2V.

5. Conclusion

Economic and environmental reasons are making EVs a reality of nowadays. The main energy storage elements used in these vehicles are batteries of different technologies. Batteries need to be charged and the more common source for that is the power grid. However, the spread use of EVs will bring consequences to the power grid, mainly in terms of load management and electric power quality, which are associated to the batteries charging systems. Many developments in the area of the batteries charging systems are being made, with the development of new topologies and control strategies. In parallel, the development of Smart Grids and the spread of micro renewable energy production systems have created a new paradigm in power grids.

This chapter assessed the electric mobility integration in the Smart Grid context, focusing different approaches to the operation of EVs batteries charging systems, their different topologies and features, modes of operation, typical waveforms, and impact in the power grid in terms of power quality. It became apparent that if the vehicles charging systems consume current with sinusoidal waveform and with unitary power factor, the THD of the currents in the power grid is drastically reduced, the RMS values of the currents are minimized, and thus the power grid voltage's THD and amplitude are less affected by the operation of the EVs batteries charging systems.

Also, in this chapter it was presented a laboratory prototype of a bidirectional EV batteries charging system, and shown some experimental results, which allows mitigating the power quality degradation of the power grid. During the batteries charging process, the voltage and the current in the batteries are controlled in order to maximize their lifespan, and at the same time consuming from the power grid sinusoidal current with unitary power factor. This batteries charging system also permits to deliver back to the power grid part of the energy stored in the batteries, which can be, in the near future, an interesting solution during short periods of time, when occur peaks of energy demand in the power grid.

Author details

Vítor Monteiro, Henrique Gonçalves, João C. Ferreira and João L. Afonso
Centro Algoritmi, University of Minho, Guimarães, Portugal

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